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Evaluating Mechanical Strength of Geopolymer Concrete: Influence of Alkali Activator Ratios and Material Proportions

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ABSTRACT: This study investigates the mechanical performance of geopolymer concrete (GPC) made with varying proportions of fly ash (FA) and ground granulated blast furnace slag (GGBS), activated by two different alkali activator ratios, 0.50 and 0.55. A total of 159 mixtures were analysed, and the compressive strength, split tensile strength, and flexural strength were evaluated after 28 days of curing at room temperature. The results indicate that the GPC with an alkali activator ratio of 0.55 achieved superior mechanical strengths, with a maximum compressive strength of 45.2 N/mm² compared to 41.5 N/mm² for the 0.50 ratio. Additionally, the study reveals that higher GGBS content correlates positively with improved compressive strength, enhancing the overall durability and sustainability of the concrete mix. A mathematical model was developed to establish predictive relationships between alkali activator concentration, FA-GGBS composition, and mechanical properties, highlighting the optimized mix design for enhanced performance.

Keywords: Geopolymer Concrete, Mathematical Modeling, Mechanical Strength, Alkali Activator Ratio, Fly Ash, and GGBS.

I. INTRODUCTION

Concrete is one of the most widely used construction materials worldwide due to its versatility, durability, and affordability. It is a composite material primarily composed of cement, water, fine and coarse aggregates such as sand and gravel, and often additional admixtures that enhance its properties. One of the unique characteristics of concrete is its ability to be moulded into various shapes while in a wet state and gain strength as it hardens, making it ideal for constructing buildings, bridges, roads, and other infrastructure. The strength of concrete is influenced by factors such as the water-cement ratio, aggregate size, and type of admixtures. These parameters can be optimized to enhance specific properties, such as compressive strength, workability, or resistance to environmental factors like extreme weather and chemical exposure. Advances in concrete technology have led to the development of sustainable alternatives, such as green concrete, which incorporates industrial waste products like fly ash (FA) or recycled aggregates to reduce the environmental impact of cement production.One of the critical attributes of concrete is its compressive strength, making it the preferred material for structural applications. However, traditional concrete is weak in tension, leading to the development of reinforced concrete, where steel bars or meshes are embedded within the concrete matrix to improve tensile strength. This combination of concrete for compression and steel for tension provides superior structural capacity, making reinforced concrete the material of choice for large-scale infrastructure projects, such as bridges, dams, and high-rise buildings.Despite its advantages, traditional concrete has a significant environmental footprint, primarily due to the high carbon emissions associated with Ordinary Portland cement (OPC) production. The cement industry is responsible for approximately 8% of global CO_2 emissions, mainly due to the calcination process, where limestone is heated at high temperatures, releasing CO_2 (Paruthi et al., 2025). In response to this challenge, innovative and eco-friendly alternatives, such as geopolymer concrete, have gained considerable attention as a sustainable substitute for conventional concrete (Jalal et al., 2025). GPC is an innovative and sustainable alternative to OPC-based concrete that does not rely on Portland cement as a binder. Instead, it relies on geopolymerization, a chemical process that activates aluminosilicate-rich materials like FA, GGBS, or metakaolin using alkaline solutions (e.g., sodium hydroxide and sodium silicate). The polymerization of silicon (Si) and aluminium (Al) present in these materials results in a stable three-dimensional aluminosilicate network that binds aggregates together, similar to the hardened matrix in traditional concrete. The use of industrial waste materials in GPC significantly reduces CO_2 emissions, making it a promising solution for sustainable construction(Jalal and Srivastava, 2025).One of the most compelling benefits of GPC is its low carbon footprint. Studies indicate that GPC can reduce carbon emissions by up to 80% compared to traditional OPC-based concrete. Additionally, GPC has demonstrated high compressive strength, often comparable to or exceeding that of conventional concrete. The rapid strength development of GPC, particularly when heat curing is applied, makes it suitable for precast applications where quick turnaround times are essential. However, GPC's performance is highly dependent on curing conditions, with factors such as temperature and humidity playing a crucial role in achieving the desired mechanical properties. Despite its advantages, the widespread adoption of GPC faces several challenges. The variability in the quality and composition of raw materials, particularly FA and GGBS, affects the consistency of the final mix, necessitating site-specific testing and optimization. Additionally, the use of alkaline activators, such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), poses safety concerns due to their corrosive nature, requiring special handling during mixing and application. Furthermore, the lack of established industry standards and design codes for GPC, along with limited familiarity among construction professionals, has hindered its large-scale adoption. The geopolymerization process, which forms the basis of GPC, involves the thermal activation of aluminosilicate materials in an alkaline environment. This process consists of three phases: dissolution, reorientation, and hardening. Initially, the reaction between the alkaline activator and the aluminosilicate source releases Si and Al species, which undergo polymerization, forming a stable aluminosilicate network. The reactivity of raw materials, concentration of the alkaline solution, and curing temperature significantly influence the strength and durability of the final GPC product.

The flowability and setting characteristics of GPC depend on its mix design and water-to-geopolymer binder ratio. While an increase in water content enhances flowability, it can reduce compressive strength, similar to traditional concrete. The rapid setting time of geopolymer mortar, compared to OPC mortar, poses challenges for workability, often requiring the use of superplasticizers to improve handling (Satheet al., 2024). The ratio of STS to CS in GPC is generally lower than that of OPC concrete, making it relatively more brittle. However, due to its highcompressive strength and sustainability advantages, GPC is considered a viable alternative for applications requiring high-strength concrete.In summary, GPC presents a promising alternative to conventional OPC-based concrete, offering significant environmental benefits by reducing CO_2 emissions and utilizing industrial by-products. While challenges such as material variability, safety concerns, and lack of industry standards remain, ongoing research and development efforts are expected to drive its adoption. As the construction industry increasingly prioritizes sustainability, GPC is poised to play a crucial role in green building technologies and environmentally responsible construction practices. In this present study, we design a Fly Ash (FA) and GGBS based GPC of grade M25 conforming mix design code IS-10262-2009(Sasikumaret al., 2023), the variation of FA in GGBS by volume is 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% & 90% named as Specimen F0, F10, F20, F30, F40, F50, F60, F70, F80 & F90 respectively, the strengthcompressive strength, split tensile strength, and flexural strength are compared from standard PCC specimenand using different mathematical modeling, the best models are evaluated using the residual (Mean Squared Error) value.Several studies have explored the strength and performance of concrete in aggressive environments. Such as, Guo et al. (2007) explore the flexural fatigue performance of concrete with 50% and 80% ground granulated blast-furnace slag (GGBS) as a cement substitute. It uses fractal theory and the GM (1, 1) grey model to evaluate crack patterns and fracture energy, finding that GGBS improves fatigue life and reduces brittleness in concrete. Chu and Kong (2021)analyzegeopolymer strength, focusing on binder-alkaline mixtures and aggregate inclusion. Using data from 159 mixtures, it identifies key strength factors and develops an accurate predictive model for better mix design. Khan et al. (2022) explore using industrial waste (GGBFS and fly ash)

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in concrete to reduce cement production and emissions. It compares AI models for predicting compressive strength, finding that the Gradient Boosting Tree (GBT) model outperforms others in accuracy. Sensitivity analysis highlights concrete aging as the most influential factor. Piro et al. (2023) explore how steel slag can partially replace normal aggregates in concrete to improve compressive strength and electrical resistivity. It uses 134 literature datasets to model the effects of key factors like curing time, cement content, and water-to-cement ratio. Among different predictive models tested, the Artificial Neural Network (ANN) outperformed others in accurately forecasting concrete strength and resistivity. Sharma et al. (2023) predict the compressive strength of GPC using an Artificial Neural Network (ANN) model, and theycompare different training algorithms and transfer functions, finding that the N7LM model performed best, while N2SCG was optimal for the training algorithm. Pradhan et al. (2023) investigate the use of rice husk ash (RHA) as a partial substitute for GGBS in alkali-activated concrete (AAC), aiming to improve sustainability by reducing industrial waste. It develops a regression model using ANN and multiple regression to predict compressive strength, finding that 10% RHA substitution enhances strength.Similarly, in this study using different mathematical modeling, the best models are evaluated using the residual (Mean Squared Error) value, which can further be used as the best predictive model for a particular strength of GPC.

This work analysed the compressive strength, split tensile strength, and Flexural strength of GPC made with varying proportions of FA and GGBS at two different alkali activator ratios (0.50 and 0.55). This will help to demonstrateits vital role in improving the mechanical properties of GPC (Shehabet al., 2016; Shilaret al., 2022)when compared to conventional concrete (CC). In addition, the exponential and logistic models are important for predicting STS and FS (Ukritnukun et al., 2020; Subash et al., 2021).

II. METHODOLOGY

In this study, Figure 1 shows the 43-grade Portland Pozzolana Cement (PPC) used in the concrete mix design. This cement was procured from the local market. Figure 2 depicts the river sand used in the experimental study, which was locally sourced and passed through a 4.75 mm IS sieve. The sand complied with the Indian Standard Specifications IS: 383-1970.

Figure 1: Portland Pozzolana Cement used in this experiment

Figure 2: Fine Aggregateused for the experiment

Initially, the sand was sieved through a 4.75 mm sieve to eliminate particles larger than 4.75 mm, and then it was washed to remove any dust. The aggregates were also sieved using a set of sieves to perform a sieve analysis. Broken stone was commonly employed as the coarse aggregate. The maximum size of the Coarse Aggregate was determined by the nature of the work. For this study, Coarse Aggregates,which were locally available with a maximum size of 20 mm and 10mm, are used.The aggregates were cleaned to eliminate dust and debris and then dried until they reached a surface-dry state. All aggregates were tested by the Indian Standard Specifications IS: 383-2016. In the present investigation, potable water and GGBS available in the local market wereused in experimental programs conforming to IS 16715: 2018.

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Figure 3: GPC Material, Sodium Silicate, and Superplasticizer used for experimentation

In this experiment, polycarboxilic ether-based superplasticizerwas used at 1.29 specific gravity. NaOH and Na_2SiO_3 are used as alkali activators to activate the solid alumino-silicate material (GGBS and FA).Where the molarity of NaOH at 14M and the specific Gravity of $Na_2SiO_3$was 1.40.Fly Ash was arranged from NTPC- Roza (ASTM C 618 Class F), conforming to IS: 3812 Grade-1(Hardjasaputra et al., 2019).For activation of solid aluminosilicate material(FA and GGBS) Na_2SiO_3 and NaOH was used in ratio of 2.4, molarity of NaOH is kept 14M,the ratio of alkaline activator to binder is analysed in two different ratios 0.50 & 0.55, for these two different ratios 0.50F10, 0.50F20, 0.50F30, 0.50F40, 0.50F50, 0.50F60, 0.50F70, 0.50F80, 0.50F90, 0.55F10, 0.55F20, 0.55F30, 0.55F40, 0.55F50, 0.55F60, 0.55F70, 0.55F80, 0.55F90 specimen is needed to cast and for better achievement of workability in fresh concrete polycarboxilic ether based superplasticizer 1.5% of binder material (Ahmedet al., 2021; Ahmedet al., 2022).

For the mix design of GPC and CC IS-10262:2019 and IS-456:2000 guidelines are followed. The mix design of PPC (CC) is tabulated in Table 1, and the mix design of GPC M25 grade is tabulated in Table 2(Sasikumar et al., 2023).Where, quantity of cement, sand, aggregate, water, Fly Ash, GGBS, Sodium silicate, Sodium Hydroxide,and admixture are provided.

Table 1: Mix Design of PPC (Control Concrete)

S. No.	Materials	Quantity per m^3
1.	Cement	360Kg
2.	Sand	795Kg
3.	20mm(CAg)	640Kg
4.	10mm (CAg)	432Kg
5.	Water	160Kg
6.	Admixture	2.52Kg

Table 2: Mix Design of Geopolymer Concrete

S. No.	Materials	Quantity per m^3	
		0.50 (AA)	0.55 (AA)
1.	Cementitious Material(GGBS+ FA)	360Kg	360Kg
2.	Sand	800Kg	795Kg
3.	20mm(CAg)	632Kg	628Kg
4.	10mm(CAg)	430Kg	428Kg
5.	Alkali Activator (AA)	180Kg	198Kg
6.	Admixture	5.4Kg	5.4Kg

The Compressive Strength (CS) test was measured through the compressive testing machine with the help of a concrete cube of size 150x150x150mm (Leong et al., 2018; Kumaret al., 2023).The CS of concrete was typically between 2,500 and 4,000 psi. Also, the Split tensile strength (STS)was measured through the compressive testing machine with the help of a pre-cast concrete cube of size 150x150x150mm, by placing the cubes diagonally.Whereas, the Flexural strength **(**FS) test was conducted through a FS testing machine with the help of a pre-cast beam of size 150x150x450mm. The FS of concrete was measured by applying force to an unreinforced concrete beam until it cracked. The amount of force required to crack the beam is used to calculate the FS.For the mathematical modeling, FA and GGBSwere taken as independent variables, say X_1 and $X_{2,}$ and the alkali activator (alkali activator and binder ratio 0.50 and 0.55) was taken separately for each different proportional variation of independent variables (Sharma et al., 2023).Variation range of X_1 corresponding to $X_2$was 0%, 10%, 20%, ... 90% i.e. 10 proportional variations is considered and the variation was checked separately over alkali activator binder ratio of 0.50 and 0.55 respectively, other parametersuch as water,FAg, CAg and superplasticizers, results in formationofGPC is taken constant for each specimen (Özkılıçet al., 2023; Satheet al., 2024).

Strength of concrete was taken as a dependent variable =Y

And the Model equations wereas follows:

$Y= mx+b$; Linear function

$Y= \log_a x$; Logarithmic function

$g(x)= f^{-1}(x)$, f(x) and g(x) be two one- one functions; Inverse function

$Y=ax^2+bx+c$; Quadratic function

$Y= ax^3+bx^2+cx+d$; Cubic function

$Y=kx^n$; Power Function

$Y=ab^x$; Growth Function

$Y= a^x$; Exponential function

$Y= 1/ (1+ e^{-x})$; Logistic Function

III. RESULTS AND DISCUSSION

The compressive strength (CS) of control concrete (CC) serves as a reference point for comparing and analysing the CS of geopolymer concrete (GPC) produced with varying proportions of fly ash (FA) and ground granulated blast furnace slag (GGBS). The CS of the control concrete after a curing duration of 28 days is established at 32.10 N/mm² (Nikoloutsopoulos et al., 2021). The compressive strength of GPC specimens at 28 days, utilizing two distinct alkali activator ratios of 0.50 and 0.55, is presented in Table 3. Results indicate that as the alkali activator ratio increases, the compressive strength also demonstrates an upward trend over the 28-day curing period (Adak et al., 2017).

Table 3: Compressive strength in (N/mm^2) of Geopolymer Concrete Specimens

S.No.	Specimen	28 days Compressive Strength (N/mm^2)	
		0.50	**0.55**
1.	F0G100	44.9	46.01
2.	F10G90	42.07	43.6
3.	F20G80	40.2	41.7
4.	F30G70	38.01	39.2
5.	F40G60	36.01	37.3
6.	F50G50	34	35.07
7.	F60G40	32.61	33.71
8.	F70G30	31.7	32.93
9.	F80G20	26.81	27.9
10.	F90G10	21.7	22.03

Figure 4 illustrates that the compressive strength (CS) of geopolymer concrete (GPC) at a curing duration of 28 days decreases progressively with an increase in the proportion of fly ash (FA). The dark grey line represents the CS of GPC activated with an alkali activator ratio of 0.55, while the light grey line denotes data for GPC with a 0.50 alkali activator ratio. Notably, the dark grey line consistently remains above the light grey line, indicating that the 0.55 alkali activator ratio yields higher compressive strength compared to the 0.50 ratio.

Furthermore, it is observed that an increase in the percentage of ground granulated blast furnace slag (GGBS) correlates positively with enhanced compressive strength. A comparison of the compressive strength of GPC at 28 days of curing with that of conventional concrete (CC) reveals that for a variation range of fly ash corresponding to GGBS from 0% to 60% with a 0.50 alkali activator ratio, GPC demonstrates greater compressive strength. In contrast, with a 0.55 alkali activator ratio, GPC achieves greater compressive strength, showing values exceeding 32.10 N/mm² for FA variations from 0% to 70%.

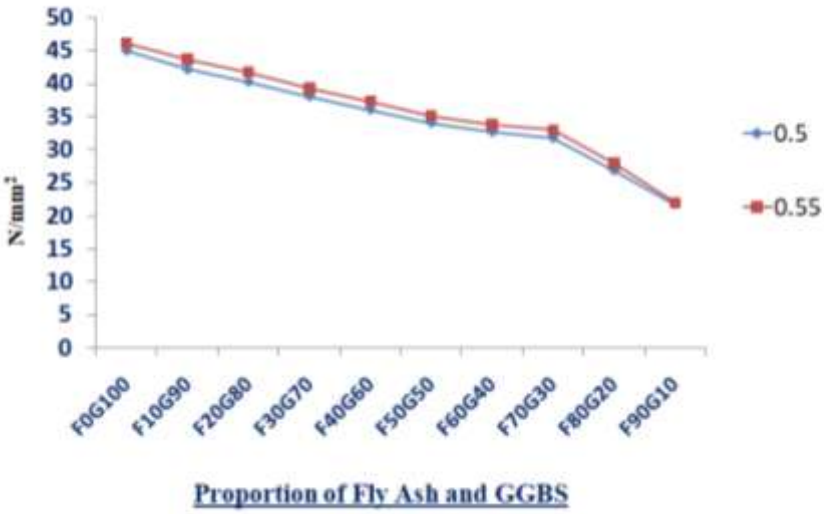

Figure 4: Line diagram of 28 days Compressive Strength

Tables 4 and 5 present a comparison of various mathematical models employed to analyse the impact of G, defined as a combination of fly ash (FA) and ground granulated blast furnace slag (GGBS), on the 28-day compressive strength of geopolymer concrete (GPC) with alkali activator ratios of 0.50 and 0.55, respectively. The models are assessed based on three criteria: coefficients (which represent the equation parameters for each model), residuals (specifically the Mean Squared Error [MSE], which quantifies the average squared difference between actual and predicted values; a lower MSE indicates a better model fit), and the p-value (which assesses statistical significance, where a p-value < 0.05 denotes a significant relationship between the combination of G and compressive strength). Upon comparison, the Power Model emerges as the optimal choice for both alkali activator ratios of 0.50 and 0.55, as it exhibits the lowest residual MSE of 0.001 and a highly significant p-value of 0.000, with coefficients of Constant = 11.016, ln(G) = 0.296 for the 0.50 ratio and Constant = 11.232, ln(G) = 0.300 for the 0.55 ratio (Saleh et al., 2018).

Table 4: Fitted Model Comparison: Significance of G on 28 days Compressive Strength at 0.50 alkali activator ratio and Error Metrics

Model	Coefficients	Residual (MSE)	p-value (Sig.)
Linear	Constant=22.257, G=0.228	2.140	0.000
Logarithmic	Constant=-1.146, ln(G)=9.428	2.060	0.000
Inverse	Constant=41.441, 1/G=-226.711	11.334	0.001
Quadratic	Constant=20.053, G=0.338, G**2=-0.001	1.690	0.000
Cubic	Constant=15.524, G=0.740 G**2=-0.010, G**3=5.279E-5	0.537	0.000
Compound	Constant=23.317, G=1.007	0.005	0.000
Power	**Constant=11.016, ln(G)=0.296**	**0.001**	**0.000**
S	Constant=3.746, 1/G=-7.403	0.006	0.000
Growth	Constant=3.149, G=0.007	0.005	0.000
Exponential	Constant=23.317, G=0.007	0.005	0.000
Logistic	Constant=0.043, G=0.993	0.005	0.000

Table 5: Fitted Model Comparison: Significance of G on 28 days Compressive Strength at 0.55 alkali activator ratio and Error Metrics

Model	Coefficients	Residual (MSE)	p-value (Sig.)
Linear	Constant=23.003, G=0.235	2.728	0.000
Logarithmic	Constant=-1.373, ln(G)=9.787	1.931	0.000
Inverse	Constant=42.891, 1/G=-237.164	11.186	0.000
Quadratic	Constant=20.369, G=0.367, G**2=-0.001	2.037	0.000
Cubic	Constant=15.645, G=0.786 G**2=-0.010, G**3=5.06E-5	0.816	0.000
Compound	Constant=24.039, G=1.007	0.005	0.000
Power	**Constant=11.232, ln(G)=0.300**	**0.001**	**0.000**
S	Constant=3.728, 1/G=-7.552	0.006	0.000
Growth	Constant=3.180, G=0.007	0.006	0.000
Exponential	Constant=24.039, G=0.007	0.006	0.000
Logistic	Constant=0.042, G=0.993	0.006	0.000

Portland Pozzolana Cement (PPC) serves as the binding material in the design of conventional concrete (CC), which is utilized as a reference for comparing split tensile strength (STS) with fly ash (FA) and ground granulated blast furnace slag (GGBS) based geopolymer concrete (GPC). The STS of the reference CC is determined to be 2.39 N/mm^2 after a curing period of 28 days at room temperature. The STS values of GPC after 28 days of curing at alkali activator ratios of 0.50 and 0.55 are presented in Table 6. The results indicate that as the alkali activator ratio increases, the STS also exhibits an increasing trend over the 28-day curing period.

Table 6: Split tensile strength of Geopolymer Concrete

S.No.	Specimen	28days Split tensile Strength(N/mm^2)	
		0.50	**0.55**
1.	F0G100	8.98	9.20
2.	F10G90	8.00	8.29
3.	F20G80	7.24	7.51
4.	F30G70	6.47	6.67
5.	F40G60	5.75	5.95
6.	F50G50	5.05	5.22
7.	F60G40	5.13	5.30
8.	F70G30	4.9	5.12
9.	F80G20	4.5	4.79
10.	F90G10	4.13	4.20

Figure 5 illustrates the split tensile strength (STS) of geopolymer concrete (GPC) after 28 days of curing at alkali activator ratios of 0.50 and 0.55. The graph reveals a decreasing trend in STS with increasing proportions of fly ash (FA), where the dark grey line represents the results for the 0.55 alkali activator ratio and the light grey line corresponds to the 0.50 ratio (Prusty et al., 2024). Notably, the dark grey line remains consistently above the light grey line, indicating that the 0.55 alkali activator ratio yields higher STS compared to the 0.50 ratio. Furthermore, it is observed that an increase in the percentage of ground granulated blast furnace slag (GGBS) correlates with an enhancement in STS. When comparing the STS values of GPC after 28 days of curing with those of conventional concrete (CC), it is evident that across the varying proportions of FA (ranging from 0% to 100% in increments of 10%), both the 0.50 and 0.55 alkali activator ratios demonstrate superior STS performancehas greater STS i.e. greater than 2.39 N/mm^{2}STS of CC for 28 days curing duration

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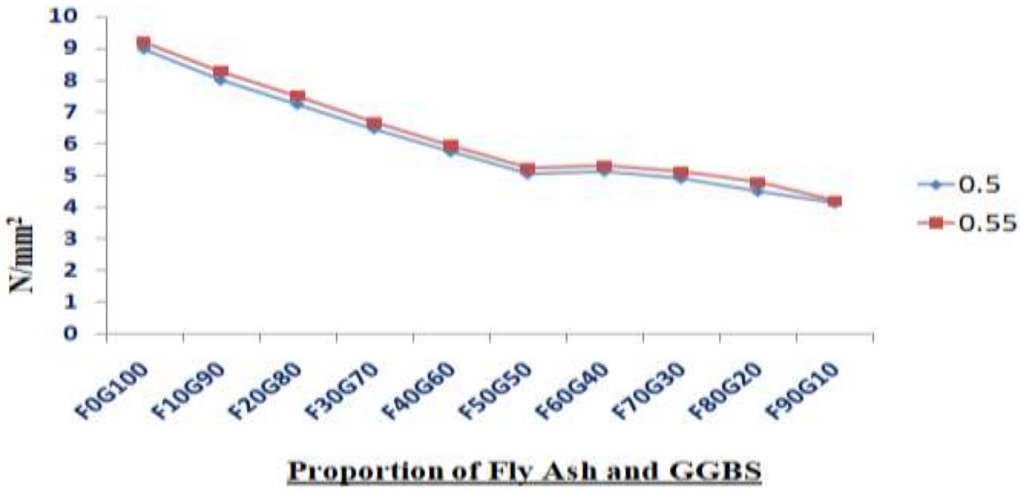

Figure 5: Line Diagram of 28 days split tensile strength

Tables 7 and 8 present a comparative analysis of various mathematical models employed to examine the influence of G (a combination of Fly Ash and Ground Granulated Blast Furnace Slag) on the 28-day split tensile strength (STS) at alkali activator ratios of 0.50 and 0.55, respectively. The evaluation of these models indicates that the Compound, Growth, Exponential, and Logistic models are the most suitable for both alkali activator ratios, as they demonstrate the lowest residual mean squared error (MSE) of 0.003 and exhibit a highly significant p-value of 0.000 (Saleh et al., 2018).

Table 7: Fitted Model Comparison: Significance of G on 28 days Split Tensile Strength at 0.50 alkali activator ratio and Error Metrics

Model	Coefficients	Residual (MSE)	p-value (Sig.)
Linear	Constant=3.196, G=0.051	0.205	0.000
Logarithmic	Constant=-1.153, ln(G)=1.880	0.778	0.002
Inverse	Constant=7.174, 1/G=-39.565	1.561	0.030
Quadratic	Constant=4.323, G=-0.005, G**2=-0.001	0.037	0.000
Cubic	Constant=3.942, G=0.029 G**2=-0.000, G**3=4.441E-6	0.033	0.000
Compound	**Constant=3.683, G=1.008**	**0.003**	**0.000**
Power	Constant=1.746, ln(G)=0.316	0.014	0.000
S	Constant=1.965, 1/G=-6.890	0.034	0.014
Growth	**Constant=1.304, G=0.008**	**0.003**	**0.000**
Exponential	**Constant=3.683, G=0.008**	**0.003**	**0.000**
Logistic	**Constant=0.272, G=0.992**	**0.003**	**0.000**

Table 8: Fitted Model Comparison: Significance of G on 28 days Split Tensile Strength at 0.55 alkali activator ratio and Error Metrics

Model	Coefficients	Residual (MSE)	p-value (Sig.)
Linear	Constant=3.349, G=0.052	0.215	0.000
Logarithmic	Constant=-1.127, ln(G)=1.928	0.778	0.001
Inverse	Constant=7.426, 1/G=-41.015	1.581	0.027
Quadratic	Constant=4.460, G=-0.003, G**2=-0.001	0.054	0.000
Cubic	Constant=4.025, G=0.035 G**2=-0.000, G**3=5.074E-6	0.049	0.000
Compound	**Constant=3.835, G=1.008**	**0.003**	**0.000**
Power	Constant=1.820, ln(G)=0.315	0.013	0.000
S	Constant=2.002, 1/G=-6.948	0.032	0.012

Growth	**Constant=1.344, G=0.008**	**0.003**	**0.000**
Exponential	**Constant=3.835, G=0.008**	**0.003**	**0.000**
Logistic	**Constant=0.261, G=0.992**	**0.003**	**0.000**

The flexural strength (FS), which is assessed through the transverse beam test, quantifies the bending strength of concrete samples. At 28 days of curing, the FS of conventional concrete (CC) was determined to be 3.58 N/mm². For geopolymer concrete (GPC) specimens cured for the same duration, the FS values at two different alkali activator ratios of 0.50 and 0.55 are detailed in Table 9. The data reveal that increasing the alkali activator ratio results in a corresponding increase in FS at the 28-day curing interval (Prusty et al., 2024).

Table 9: Flexural strength in (N/mm^2) of Geopolymer Concrete Specimens

S.No.	Specimen	28 days Flexural Strength (N/mm^2)	
		0.50	**0.55**
1.	F0G100	11.21	11.49
2.	F10G90	10.30	10.68
3.	F20G80	9.68	10.04
4.	F30G70	9.02	9.30
5.	F40G60	8.06	8.35
6.	F50G50	7.75	7.99
7.	F60G40	7.17	7.41
8.	F70G30	7.13	7.49
9.	F80G20	6.67	6.94
10.	F90G10	5.46	5.55

Figure 6 illustrates the flexural strength (FS) of geopolymer concrete (GPC) after 28 days of curing. An analysis of the data reveals a decreasing trend in FS with increasing proportions of fly ash (FA). The dark grey line represents GPC activated with an alkali activator ratio of 0.55, while the light grey line corresponds to an alkali activator ratio of 0.50. Notably, the dark grey line is positioned slightly above the light grey line, indicating that an alkali activator ratio of 0.55 yields a higher FS compared to the 0.50 ratio. Additionally, it was observed that higher percentages of ground granulated blast furnace slag (GGBS) correlate with increased FS (Prusty et al., 2024). When comparing the FS of GPC at this 28-day curing period with that of conventional concrete (CC), it is evident that for the range of FA compositions corresponding to GGBS from 0% to 100%, both alkali activator ratios (0.50 and 0.55) resulted in FS values exceeding 3.58 N/mm², which is the FS of CC at the same curing duration.

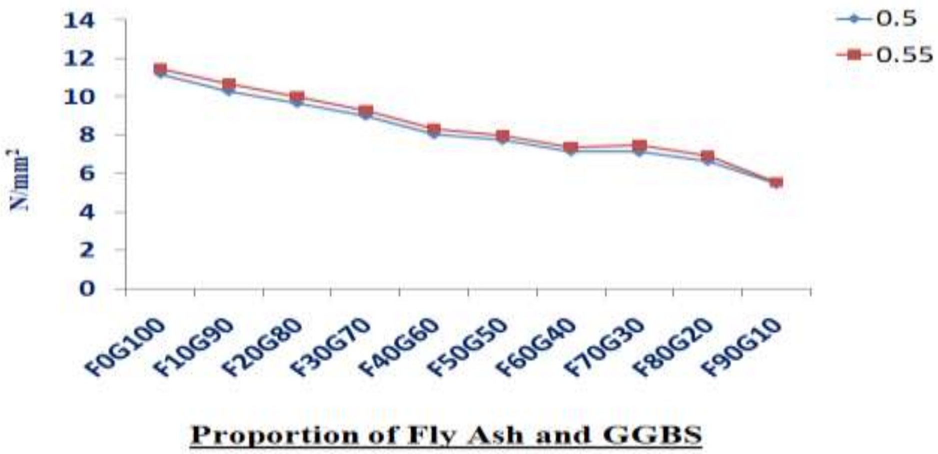

Figure 6: Line Diagram of 28 days Flexural Strength

Table 10: Fitted Model Comparison: Significance of G on 28 days FlexuralStrengthat 0.50 alkali activator ratio and Error Metrics

Model	Coefficients	Residual (MSE)	p-value (Sig.)
Linear	Constant=5.053, G=0.058	0.099	0.000
Logarithmic	Constant=-0.349, ln(G)=2.254	0.503	0.000
Inverse	Constant=9.738, 1/G=-50.989	1.325	0.006
Quadratic	Constant=5.498, G=0.036, G**2=-0.000	0.083	0.000
Cubic	Constant=4.825, G=0.095, G**2=-0.001, G**3=7.840E-6	0.065	0.000
Compound	**Constant=5.451, G=1.007**	**0.002**	**0.000**
Power	Constant=2.704, ln(G)=0.287	0.004	0.000
S	Constant=2.286, 1/G=-6.746	0.015	0.002
Growth	**Constant=1.696, G=0.007**	**0.002**	**0.000**
Exponential	**Constant=5.451, G=0.007**	**0.002**	**0.000**
Logistic	**Constant=0.183, G=0.993**	**0.002**	**0.000**

Table 11: Fitted Model Comparison: Significance of G on 28 days FlexuralStrengthat 0.55 alkali activator ratio and Error Metrics

Model	Coefficients	Residual (MSE)	p-value (Sig.)
Linear	Constant=5.243, G=0.060	0.122	0.000
Logarithmic	Constant=-0.370, ln(G)=2.332	0.502	0.000
Inverse	Constant=10.085, 1/G=-53.310	1.333	0.005
Quadratic	Constant=5.615, G=0.041, G**2=-0.000	0.117	0.000
Cubic	Constant=4.866, G=0.108, G**2=-0.001, G**3=8.733E-6	0.098	0.000
Compound	**Constant=5.638, G=1.007**	**0.002**	**0.000**
Power	Constant=2.7773, ln(G)=0.289	0.004	0.000
S	Constant=2.323, 1/G=-6.876	0.014	0.001
Growth	**Constant=1.730, G=0.007**	**0.002**	**0.000**
Exponential	**Constant=5.638, G=0.007**	**0.002**	**0.000**
Logistic	**Constant=0.177, G=0.993**	**0.002**	**0.000**

Tables 10 and 11 present a comparative analysis of the various mathematical models employed to evaluate the influence of G (a blend of Fly Ash and GGBS) on the 28-day flexural strength at alkali activator ratios of 0.50 and 0.55, respectively. Among the models assessed, the Compound, Growth, Exponential, and Logistic models emerged as the most suitable for both alkali activator ratios, as they consistently exhibited the lowest residual mean squared error (MSE) of 0.002 and a highly significant p-value of 0.000 (Saleh et al., 2018; Sharma et al., 2023).

IV. CONCLUSION

The study demonstrates that geopolymer concrete (GPC) incorporating varying proportions of fly ash (FA) and ground granulated blast furnace slag (GGBS) exhibits significant mechanical strength advantages over traditional concrete. Higher alkali activator ratios (0.55) lead to enhanced compressive strength, split tensile strength, and flexural strength, showcasing the effectiveness of GGBS in improving GPC properties. The research successfully establishes predictive mathematical models that correlate the mixture design with mechanical performance, providing valuable insights for optimizing GPC formulations. Overall, GPC emerges as a promising sustainable alternative to conventional cement-based concrete, contributing to reduced environmental impact while delivering superior structural performance. Future research should focus on exploring long-term durability and various curing methods to further validate its potential in construction applications.

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